Using Periodic Systems to Model Hand-Haptic Interface Coupling

Diana Herrera, Jean-Loup Florens, Alina Voda

Using Periodic Systems to Model Hand-Haptic Interface Coupling

Diana Herrera * **Jean-Loup Florens** * **Alina Voda** **

* *Laboratoire ICA, Grenoble INP, 46 Avenue Félix Viallet, 38031, Grenoble Cedex 1, France (e-mail: diana.herrera@imag.fr, florens@imag.fr)*
** *Gipsalab Control Department, ENSIEG BP 46, Rue de la Houille Blanche. 38402 Saint Martin d'Hères, France (e-mail: alina.voda@gipsa-lab.grenoble-inp.fr)*

Abstract: The analysis of hand-haptic interface coupling as a whole system is an important question for the development of high quality haptic devices and their use in dynamical tasks where the haptic modality plays an important role. In this paper, we propose a periodic system, the Van der Pol equation, as a first approach for modeling hand-haptic interface coupling. In particular, we are interested in periodical gestures or tasks and the interaction models able to generate them. We analyze this system and we identify its parameters from the data position acquired during simulation. In this paper we present some preliminary results.The identification of this parameters should lead as to improve haptic systems performances.

Keywords: Human Machine Interface, Real Time Systems, Parameter Identification, Least-squares Method, Periodic Motion, Van der Pol Equation.

1. INTRODUCTION

The term Haptics involves an interaction or a physical contact performed with an intention of perception, exploration or manipulation. This interaction can occur between a human hand and a real object, an end effector and a real object, a human hand and a simulated object (via a haptic interface device) or several combinations between humans or robots and real or virtual objects. See Salisbury et al. (2004).

To manipulate a haptic interface the presence of a human operator is necessary and, in most cases, the body part that interacts with the haptic interface is the hand. Hence the importance of studying and analyzing the interaction between the hand of the human operator and the used haptic interface.

Haptic systems design usually relies on two complementary but different types of considerations: On the one hand, most of the studies are focused only on the properties of the "object", i.e. the haptic device and the simulated virtual object. In these cases, the related criteria are based on the haptic simulator's ability to reproduce the properties of the object without considering the properties of the human, see Colgate and Brown (1994). The essential limit of these approaches is that the part of the object which actually interacts with the hand, can never be precisely known.

On the other hand, a complementary approach considers the properties of the human. This approach is related to the field of psychophysics and perception in which the object of study is the human. In this case, we assume that the human properties allow to identify the requirements of the haptic system for example in terms of bandwidth, see Couroussé and Florens (2007). However, this approach presents the symmetrical limitations of the previous one, since it is not easy to characterize the human as an open system and, in addition, the observation of human mechanical invariants is far more difficult.

In order to develop high-performance haptic systems, it is necessary to have a better knowledge of the hand-haptic interface close coupling in natural situation, at least for some representative elementary tasks. To better understand what happens during the haptic interaction, it is necessary not to consider the object or the human as separate systems, but as a whole system in which the two interacting parts are not separable. Following this idea, we consider the gestural movements produced when manipulating the virtual object as the result of the evolution of an autonomous (or quasi-autonomous) system defined for a finite duration and constituted of a part of the human and a part of the object. This "Temporary Hybrid System" (THS) hypothesis was presented and described in Florens and Urma (2006), Florens et al. (2006). The analysis of the hand-haptic interface coupling as a whole system according to the THS hypothesis, should allow us to establish a new framework to define the technical performances of haptic interfaces and should give us new knowledge about the human sensorimotor system function. It should help us improve the design of high quality haptic devices.

In particular, we are interested in periodical gestures or tasks and in the interaction models able to generate them. Indeed, periodical phenomena are widespread in the inanimate world of physics as in alive organisms, see Bergé et al. (1988). Periodical gestures are very common in the every day life, for example in music, when playing an instrument and in other tasks, especially in those performed with a tool such as hammering or screwing. Those periodical tasks, as well as several devices and phenomena, present an oscillating behavior. For this reason, it is possible to use oscillator equations to model them, see Mottet and Bootsma (1999).

In this paper, we propose a first approach to validate the THS hypothesis carrying out some experiences to get more precise qualitative and quantitative data of this system using parameter identification. These experiences will be implemented using a high bandwidth haptic simulator and will concern the performance of some specific elementary tasks, such as periodical movements. For each specific task, the general methodology consists in setting up an adequate object simulation. Then, we elaborate a model of the human that matches with the observed behavior when it is coupled to the object. Among the analysis tools, we will use parameter identification techniques based on the Least Squares Method (LSM).

As a first approach for modeling hand-haptic interface coupling we propose a periodic system such as the Van der Pol equation. We analyze this system and we identify its parameters from the position data acquired during real time simulation using the LSM.

The paper is structured as follows. In section 2, we describe the THS concept used for the analysis of the human hand-haptic interface interaction. In Section 3, we examine the interest of periodical movements for analyzing the hand-virtual object coupling and we propose the Van der Pol equation as a first approach for this analysis. Then, in Section 4, we present the method used to identify the Van der Pol system parameters using the position data obtained during real time simulation. In Section 5, we describe the configuration setup of the haptic simulator used for the experiments. In section 6, we present the experimental protocol used for data acquisition during the real time simulations. In Section 7, we discuss the preliminary experimental results and finally we conclude and we present the future work in Section 8.

2. MODELING THE HUMAN-OBJECT INTERACTION

2.1 The "THS" concept

To analyze the interaction between the human hand and a haptic device we use the approach proposed by Florens et al. (2006). This approach considers a quasi-autonomous physical system called "Temporary Hybrid System" (THS) composed by a limited part of the human mechanics and a part of the object, situated near the borderline between the human and the object. This THS is an evolutive system and its physical parameters are the result of several combinations of the human and the object dynamics as defined by Florens and Urma (2006). A general representation of this kind of system is shown in Fig. 1.

The THS concept can be applied to different situations of interaction where the observed behavior can not be easily described by the constitution of two distinct models

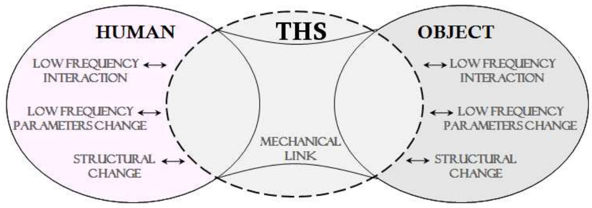

Fig. 1. General representation of a Temporary Hybrid System

involving only the human or the object. These situations concern in particular the non permanent contacts, as those that appear between the skin and the object. In the case of rigid objects, the small scale properties of the two surfaces are determinant and this type of interaction produces generally high frequency phenomena. The typical case concerns the friction interaction. In this case, the interest of the THS approach relies on the possibility to represent the interaction properties by a functional model. The example described above can be transposed to the case of a tool-object interaction during permanent grasp. This kind of task corresponds more precisely to the possibilities of the usual haptic interfaces which present a limited number of degrees of freedom and a predefined handle morphology. This case corresponds to the handled tool situation characterized by the rigid coupling between the hand and the tool. Like in the previous situation, this rigid or quasi-rigid structure may produce high frequency forces and oscillatory movement induced by the tool-object interaction. A typical example in the domain of musical instruments are the bowed instruments and the percussion instruments with light drumsticks.

The THS hypothesis is an original approach because few technological or psychophysical researches have considered the hand-haptic device system as a whole system where the two interacting parts are not separable. We aim to realize the first functional models of a THS "hand-haptic interface".

2.2 The THS in the mediated interaction

In the case of the human-virtual object interaction, the interaction between the human and the object does not occur directly but through the haptic interface. Then, in this situation, the THS is composed by a part of the virtual environment (a part of the virtual object) as well as a part of the real environment (a part of the human), and as the interaction between these two environments is mediated by the haptic device, this device is also a component of the THS as shown in Fig. 2.

3. MODELING THE INTERACTION IN THE CASE OF PERIODIC MOVEMENTS

3.1 Periodic movements

In the presented work, we apply the THS concept to the analysis of periodic movements. We consider that a periodic movement is a motion which occurs over and over and requires the same period of time for each occurrence. A common example of this kind of motion is "tapping". As defined by Couroussé et al. (2006), tapping is the action

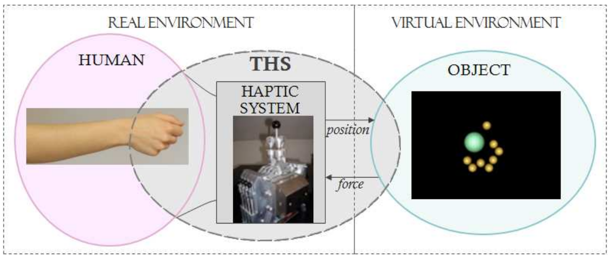

Fig. 2. Temporary Hybrid System in the simulated situation

of applying repetitive percussions on a sounding object or surface, either with the finger or using a tool such a hammer or a pen.

We can consider two opposite cases of oscillatory phenomena in gesture. The first case concerns the oscillations produced by the human motor system in which the temporary characteristics are completely determined by the action. Such situation exists in particular in the case of slow movements. The second case concerns the oscillations produced by a specific configuration of the object in which the energy is provided by the gesture. An example is the oscillation of a chalk on a blackboard when it is driven and held in a certain way. In this case, the human motor system behaves like a constant speed generator and the combination of the hand impedance and the non linear friction of the chalk produces the oscillations.

For the experiments described in this paper, we limited our work to the first of the two cases described above, where the oscillations are produced by the human motor system and we limited the simulated object to a simple linear damping-spring element.

3.2 Modeling

Modeling rhythmic human movements as self-sustained oscillators has become an important issue in motor control research. See Beek and Beek (1988), Mottet and Bootsma (1999), Mottet and Bootsma (2001). These approaches are based on the assumption that the central nervous system employs limit-cycle dynamics to produce rhythmic movements. In this framework rhythmic movements are modeled as oscillators represented by second order ordinary differential equations, see Delignières et al. (1999). Our objective is to find a simple model able to reproduce the observed effects in the case of periodic movements generated by the human.

The simplest model that generates stationary oscillations is the conservative harmonic oscillator :

$$m_0\ddot{x} + kx = f \tag{1}$$

where m_0 is the mass, k is the spring constant, x is the displacement and f is the force.

In this model the amplitude is determined by the initial conditions. A fundamental limitation of this kind of system is the loss of its properties of generating a periodic behavior once it is coupled to another system presenting dissipation. However, the conservative oscillator can be used as a simple model of sinusoidal motion generation if its impedance (mass m_0) is much higher than the impedance of the load. We should use a model allowing us to overcome this limitation. This model should present the following properties: independence regarding the initial state, robustness regarding the perturbations and the coupling to external dissipative or non dissipative systems. We add a last property related to the evolution equation of the system. This equation should be linear with respect to its parameters. This property allows to perform the parameter identification based on the LSM, see Poignet and Gauthier (2000).

3.3 The Van der Pol equation

The Van der Pol equation (2) describes a system considered as a simple model able to generate periodic phenomena with a fixed amplitude that depends only on its parameters and not on the initial state. As a first approach, we propose the Van der Pol oscillator to model our system, i.e. the hand-haptic interface coupling during periodic movements.

The Van der Pol oscillator equation is defined by:

$$\ddot{x}(t) - \gamma_0\left[1 - \frac{x^2(t)}{x_0^2}\right]\dot{x}(t) + \omega^2 x(t) = F(t) \tag{2}$$

where γ_0 is the coefficient of friction, $\gamma_0 > 0$, x_0 is the reference amplitude, ω is the frequency and $F(t)$ is the input force. See Bergé et al. (1988). In the case of an autonomous Van der Pol oscillator $F(t) = 0$.

This kind of system can be modeled using the Cordis-Anima formalism for physical modeling proposed by Cadoz et al. (1993) and described in Section 5.

4. PARAMETER IDENTIFICATION

The general identification method consists in proposing a dynamical model and identifying its parameters from the system measurements i.e. position data.

4.1 Least Squares Method (LSM)

As a first approach to identify the parameters of the proposed model, we present the LSM based on a linear regression equation. This method can be used assuming that the model equation is linear with respect to its parameters, see Gautier and Poignet (2001). The aim is to identify the system parameters from measurements of the oscillation amplitude. However, we could use any other measure, such as the velocity, depending on the technical dispositions and the implemented experiment.

If all states are considered to be measured, *i.e.* $x(t)$, $\dot{x}(t)$ and $\ddot{x}(t)$ are known for all t and $F(t) = 0$, the Van der Pol equation (2) can be formulated as a linear regression equation:

$$x(t) = -\frac{1}{\omega^2}\ddot{x}(t) + \frac{\gamma_0}{\omega^2}\dot{x}(t) - \frac{\gamma_0}{\omega^2}\frac{x^2(t)}{x_0^2}\dot{x}(t) \tag{3}$$

This linear regression can be written in a general form as:

$$y_0(t) = \theta^T\phi(t) \tag{4}$$

where:

$\phi(t)$ is the vector of lagged input-output data,
$\theta(t)$ is the parameter vector,
and $y_0(t)$, the observed variable.

In the case where an external perturbation $v(t)$, i.e. white noise, is present in the system, the observed variable $y(t)$ is given by:

$$y(t) = y_0(t) + v(t) \tag{5}$$

The equation (5) describes the observed variable $y(t)$ as an unknown linear combination of the components of the observed vector $\phi(t)$ added to the noise $v(t)$, see Ljung and Söderström (1983).

In our case, the observed variable $y(t)$ corresponds to the vector of measured position data $x(t)$. If we consider that the three parameters of the Van der pol equation (γ_0, ω and x_0) are unknown, the regressor $\phi(t)$ and the parameter vector θ are given by:

$$\phi(t) = (-\ddot{x}(t),\ \dot{x}(t),\ -x^2(t)\dot{x}(t))^T \tag{6}$$

$$\theta = (\frac{1}{\omega^2},\ \frac{\gamma_0}{\omega^2},\ \frac{\gamma_0}{\omega^2 x_0^2})^T \tag{7}$$

This linear regression can be solved using a classical identification method such as the LSM. See Ljung and Söderström (1983). The parameter vector θ is estimated from the measures of $y(t)$, $\phi(t)$ with $t = 1, 2, \ldots N$. A common way is to choose this estimation by minimizing the criterion function given by:

$$V_N(\theta) = \frac{1}{N}\sum_{1}^{N} \alpha_t \left[y(t) - \theta^T\phi(t)\right]^2 \tag{8}$$

where α_t is a sequence of positive numbers. Then, we minimize this criterion function with respect to θ.

In this case, we identify the system parameters from the measured position data. The parameter vector θ is estimated from the measurements of $x(t)$, and the vector $\phi(t)$ for all t. The velocity $\dot{x}(t)$ and the acceleration $\ddot{x}(t)$ are estimated from the acquired data position $x(t)$ using a numerical differentiation method.

5. IMPLEMENTATION

5.1 Configuration Setup

For the experiments described in this paper, we use a completely synchronous simulation architecture created in the ICA laboratory, the haptic simulator ERGON_X. See Florens et al. (2004). It is a compact and transportable simulator that allows to use high simulation frequencies up to 44100 Hz. This simulator is composed by a host computer (Linux OS) with graphical board, a DSP board placed in the PCI port of the host machine, a Force Feedback Gestural Transducer ERGOS (TGR) and a visual display. The DSP board is the core of this architecture, we use a TORO board manufactured by Innovative Integration.The basic features of this board are a DSP Texas Instruments TMS320C6711 150MHz with 32 Mbytes SDRAM, a 4/32 bit PCI bus (3.3/5V, 33MHz), 16 independent A/D and D/A channels with 250kHz maximum sample rate and 16 bit precision.

The simulation process is executed on the DSP integrated to this board and is isolated from the host computer and from constraints of the process execution in real time.

The ERGOS System used for these experiments is a four axis system that supports different manipulator morphologies. In this case, we use the piano keys morphology.

A complete diagram of the used configuration as well as the communication between the DSP and the host is shown in Fig. 3.

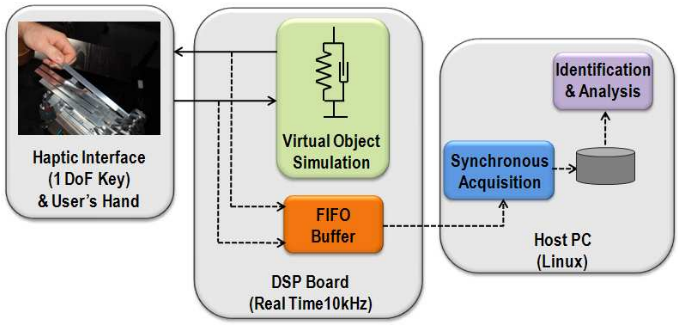

Fig. 3. Used configuration

5.2 Data Acquisition

As shown in Fig. 3, we added to our system an acquisition protocol to measure position data from the TGR key when it is manipulated by an operator. To implement this protocol, it is necessary to consider that the data must be transmitted in such a manner that it will guarantee a smooth transfer of all measured data. This will ensure the data integrity during each memory read and write cycle. For this data transfer, the maximum simulation frequency is 10kHz to be able to recover position data for each simulation step. While simulating, this acquisition protocol allows us to save 50000 samples of position data corresponding to a 5 seconds performance. These samples are saved in a file and they are used to identify the system parameters.

5.3 Modeling the Virtual Object

The virtual environment models are built based on the Cordis-Anima formalism based on Newtonian mechanics and used for physical modeling, see Cadoz et al. (1993). This formalism is also used in the domain of musical synthesis based on the representation of virtual instruments, see Florens (2002).

The Cordis-Anima objects are build by assembling functionals blocs, called modules that constitute the physical pieces of the model (masses, springs, dampers, etc).

For the experiments described in this paper, the used model is represented only by a REF module composed by a spring of K stiffness and a damper of B damping linked to the TGR and to a SOL module that represents the ground as shown in Fig. 3. Then, the equation of the virtual model is given by:

$$F = KX + B\dot{X} \tag{9}$$

where F is the virtual force and X is the virtual position. This model is implemented using the Texas Instruments Code Composer Studio tool suite, which is intended for the development of various applications running on the target or host. The simulation of the model is executed on the DSP.

6. EXPERIMENTS

6.1 Experimental Protocol

We performed a preliminary experiment in order to obtain data position from the TGR during real time simulation and while it was manipulated by a subject.

The experiments were performed by three subjects. The results shown in this paper correspond to subject 1.

The subjects were asked to grip one TGR key and to move it up and down performing a linear and vertical periodic movement and trying to keep constant amplitude and frequency. They were helped by the real time visualization of the TGR key position, i.e. a visual environment developed in the host computer. This visualization should help people perform the movement during the experiences. The amplitudes and frequencies were not fixed, the subjects were able to choose them.

While the real time simulation was executed at a sampling frequency of 10kHz, using the acquisition protocol, we saved the position data corresponding to a 5 seconds duration (50000 samples) for each experiment in a text file.

In order to compare the identification results, we chose to simulate the virtual object with some basic differences in its parameters. We defined three parameter groups as shown in Table 1. We began the experiment with the parameter group (1a) corresponding to a defined value of stiffness K and a low value of damping B. Keeping the same value of the stiffness K we increased the damping B (1b) until a high value (1c).

Table 1. Parameter groups defined for the experiments

Experiment	K	B
(1a)	0.1	10
(1b)	0.1	50
(1c)	0.1	100

For each subject, we took about one hour to perform the whole experiment, including the learning and the training periods as well as the task execution and the measurements. The three subjects executed the proposed task successfully, even if the variation of the virtual object damping produced an important waste of energy that made the subject tired very fast.

7. RESULTS

The position data measured during the experiments were analyzed using MATLAB. These data were obtained during the real time simulation of the virtual model described in Section 5.3 for the parameter group (1b) defined in Table 1. The position data $x(t)$ obtained from the real time system were noisy and presented a continuous component as shown in Fig. 4. These data were high-pass filtered to remove the continuous component and we obtained the signal $x_1(t)$. They were also low-pass filtered to remove the noise and we obtained the signal $x_2(t)$. In both cases we used a non causal zero phase digital filter (Butterworth filter in both the forward and reverse direction).The filtered signals $x_1(t)$ and $x_2(t)$, corresponding to the position data $x(t)$ after the highpass and lowpass filtering respectively, are shown in Fig. 5.

The filtered position data $x_2(t)$ were used for the parameter identification and to calculate the velocity $\dot{x}(t)$ and the acceleration $\ddot{x}(t)$. In fact, we need to calculate $\dot{x}(t)$ and $\ddot{x}(t)$ to build the vector $\phi(t)$. They were calculated using the central difference algorithm for derivatives. It is important to consider that the signal noise increases for the first and the second derivative. This noise enhancement makes the parameter identification difficult. It is not possible to achieve the identification without smoothing or filtering the noisy signals. It is essential to use differentiation in combination with sufficient smoothing or filtering, in order to control the signal to noise ratio.

We obtained an estimation of the parameter vector $\theta(t)$ (7) and the parameters γ_0, x_0 and ω. These results are shown in Table 2. We can observe that we obtained positive values of γ_0. The results show that we are beyond the Hamiltonian model and that we are identifying a system where there is an energy exchange and dissipation.

Table 2. Estimation results of parameters x_0, γ_0 and ω_0 for subject 1

Experiment	x_0	γ_0	ω
(1a)	$5.5629 \cdot 10^4$	0.6722	31.9198
(1b)	$6.4887 \cdot 10^4$	0.6120	35.6769
(1c)	$5.0384 \cdot 10^4$	0.2771	32.5601

The parameter γ_0 shows the degree of non conservability of the system. We observed that as a function of the virtual object parameters K and B, the parameter is different from zero and decreases when we increment the virtual object damping B.

We also observed that the signal amplitude is about $2 \cdot x_0$ and the estimated frequency corresponds to the oscillation frequency observed in Fig. 5. To verify the behavior of the identified system (2) with the estimated parameters, using MATLAB and Simulink we introduced these parameters into the model and we simulated the system. We observed the behavior of the Van der Pol equation as shown in Fig. 6.

8. CONCLUSION

The work described in this paper constitutes only a preliminary approach for the analysis of hand-haptic interface coupling using parameter identification.

We used the Van der Pol model because of its simplicity. However, this model can only be used in the cases where the periodic gesture is executed with very simple objects such as the spring-damping element. This situation provides few information. We will analyze other periodic situations, such as tapping, that presents a strong non linear load. This kind of situation should give us more

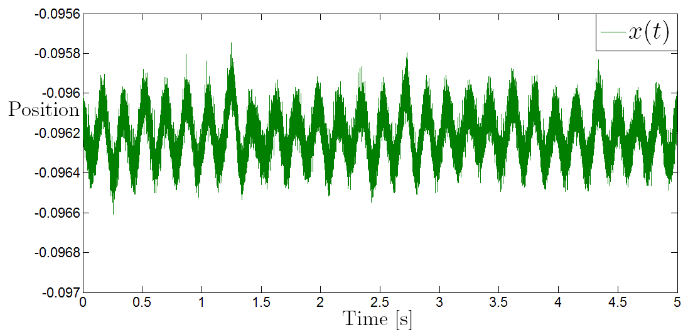

Fig. 4. Position data for experiment (1b) with $K = 0.1$ and $B = 50$

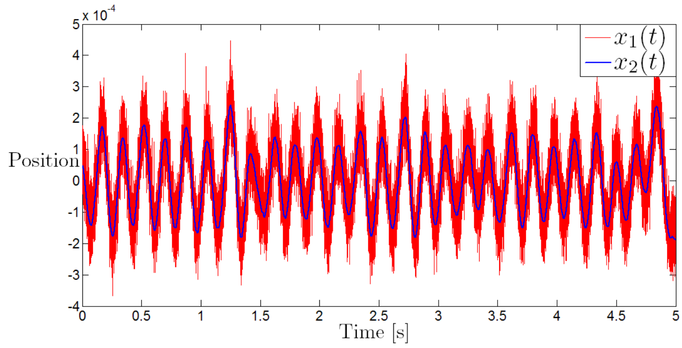

Fig. 5. Filtered position data for experiment (1b) with $K = 0.1$ and $B = 50$

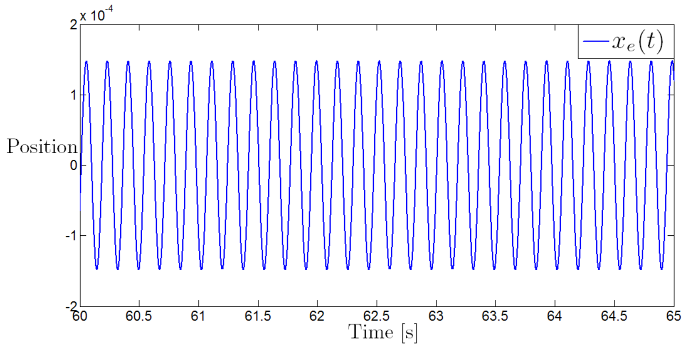

Fig. 6. Position obtained simulating the Van der Pol model in MATLAB using the estimated parameters for case (1b)

informations about the system. We aim also to bring this analysis beyond the periodic situations. We will implement some new experiments defining a largest variation of the object parameters and repeating the experiments with more subjects.

The final results of the analysis of hand-object coupling and the parametric identification should be used to define some new criteria and specifications to improve the development of high quality haptic interfaces.

ACKNOWLEDGEMENTS

This work was supported in part by a grant from "Region Rhône Alpes", France in the framework of "CIBLE" projects.

REFERENCES

Beek, P.J. and Beek, W.J. (1988). Tools for constructing dynamical models of rythmic movement. *Human Movement Science*, 7, 301–342.

Bergé, P., Pommeau, Y., and Vidal, C. (1988). *L'ordre dans le chaos*. Hermann edition.

Cadoz, C., Luciani, A., and Florens, J. (1993). Cordis-anima : a modeling and simulation system for sound and image synthesis - the general formalism. *Computer Music Journal*, 17(1).

Colgate, J.E. and Brown, J.M. (1994). Factors affecting the z-width of a haptic display. In *Proceedings of the IEEE International Conference on Robotics & Automation*, 3205–10. San Diego,CA.

Couroussé, D. and Florens, J.L. (2007). Functional analysis of haptic devices. In *Proceedings of Enactive 07, 4th International Conference on Enactive Interfaces*, 57–60. ACROE-ICA, Grenoble, France.

Couroussé, D., Florens, J.L., and Luciani, A. (2006). Effects of stiffness on tapping performance. In *Symposium on haptic interfaces for virtual environment and teleoperator systems (HAPTICS 2006)*, 421–428. IEEE, Alexandria, Virginia, USA.

Delignières, D., Nourrit, D., Deschamps, T., Lauriot, B., and Caillou, N. (1999). Effects of practice and task constraints on stiffness and friction functions in biological movements. *Human Mouvement Science*, 18, 769–793.

Florens, J.L., Luciani, A., Castagne, N., and Cadoz, C. (2004). Ergos: a multi-degrees of freedom and versatile force feedback panoply. In *EuroHaptics 2004*, 356–360. Germany.

Florens, J.L. and Urma, D. (2006). Dynamical issues at the low level of human / virtual object interaction. In *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'06)*, 315–320.

Florens, J.L., Voda, A., and Urma, D. (2006). Dynamical issues in interactive representation of physical objects. In *EuroHaptics*, 213–219. Paris, France.

Florens, J. (2002). Real time bowed string synthesis with force feedback gesture. invited paper forum acousticum. Sevilla, Spain.

Gautier, M. and Poignet, P. (2001). Extended Kalman filtering and weighted least squares dynamic identification of robot. *Control Engineering Practice*, 9, 1361–1372.

Ljung, L. and Söderström, T. (1983). *Theory and practice or recursive identification*. MIT Press, Cambridge, MA.

Mottet, D. and Bootsma, R.J. (2001). The dynamics of rythmical aiming in 2d task space: Relation between geometry and kinematics under examination. *Human Mouvement Science*, 20, 213–241.

Mottet, D. and Bootsma, R.J. (1999). The dynamics of goal-directed rhythmical aiming. *Biological Cybernetics*, 80, 235–245.

Poignet, P. and Gauthier, M. (2000). Comparison of weighted least squares method and extended Kalman filtering methods for dynamic identification of robots. In *Proceedings of the IEEE International Conference on Robotics and Automation*. San Francisco, CA.

Salisbury, K., Conti, F., and Barbagli, F. (2004). Haptic rendering: Introductory concepts. *Computer Graphics and Applications, IEEE*, 24, 24–32.